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SEEING DOUBLE: STRONG GRAVITATIONAL LENSING OF HIGH-REDSHIFT SUPERNOVAE

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ABSTRACT

With the advent of large, deep surveys, the observation of a strongly gravitationally lensed supernova becomes increasingly likely. High-redshift surveys continue apace, with a handful of type Ia supernovae observed to date at redshifts of one or greater. In addition, a satellite (the *Supernova/Acceleration Probe*[SNAP]) has been proposed dedicated to observing thousands of supernovae per year out to a redshift of 1.7. Although it is exceedingly unlikely that we will see a multiply-imaged supernova from ongoing surveys, we find that SNAP would observe at least eight such events per year. Since having a standard candle is inessential to most lensing studies, SNAP's large sample of type II supernovae contributes to this rate. Each case of strong lensing allows for a precise determination of time delays, image separations, and relative image magnifications, and the SNAP strong-lensing database will offer measures of Ω_m, Ω_Λ, and H_0, *independent* of SNAP's primary goal of establishing the distance-redshift relation. These systems also constrain models for the matter density profiles of galaxies and clusters. Furthermore, lensed type Ia supernovae afford the opportunity to break the mass-sheet degeneracy found in many lensing measurements.

Subject headings: cosmology: observations—cosmology: theory—gravitational lensing—supernovae: general

1. INTRODUCTION

Type Ia supernovae (SNe) have become an extremely powerful cosmological probe. They appear to be very good (calibrated) standard candles (Riess, Press, & Kirshner 1996a; Branch 1998), and because of this they enable a direct measurement of the distance-redshift relation, and hence the expansion history of the universe (Colgate 1979; Goobar & Perlmutter 1995). At present on the order of 100 high-redshift SNe have been observed, and surveys are adding dozens of type Ia's a year at increasingly high redshifts. Results from these surveys indicate that the universe's expansion is accelerating (Riess et al. 1998; Perlmutter et al. 1999), and this discovery has led to a tremendous amount of excitement in the cosmological community. In particular, there is great interest in the SuperNova/Acceleration Probe (SNAP), a satellite dedicated to searching for and observing high-z SNe.[1] The primary objective of the mission would be to measure cosmological parameters to unprecedented accuracy, enabling, for example, the distinction between a cosmological constant and a "quintessence" component (Huterer & Turner 1999). The satellite would achieve this by observing over 2000 type Ia SNe per year, getting a complete light curve, multiple colors, and a spectrum at maximum light for each one, and thereby measuring the distance-redshift relation out to $z = 1.7$ to unprecedented precision.

Gravitational lensing can influence the observed brightness of high-z SN data. The impact of small shifts in the brightnesses of SNe due to weak lensing has been extensively explored, both as a potential source of noise (Kantowski, Vaughan, & Branch 1995; Frieman 1997; Wambsganss et al. 1997; Holz 1998), and as a source of science (Metcalf & Silk 1999; Holz 1999; Seljak & Holz 1999; Metcalf 1999). In this paper we focus on the possibility for strong lensing of SNe, leading to multiple images of a given source. While this possibility has also been discussed (Schneider & Wagoner 1987; Linder, Schneider, & Wagoner 1988; Kovner & Paczyński 1988; Porciani & Madau 2000), we consider strong lensing in the age of large-scale, high-z SN surveys (see also Wang (2000)). Although current surveys are unlikely to produce a case of multiple imaging, we find that SNAP would be expected to see numerous such events. In addition, SNAP would be well suited to do extensive characterization of the events, bringing the very real possibility of science from multiply-imaged SNe in the foreseeable future.

2. LIKELIHOOD OF MULTIPLY-IMAGED SUPERNOVAE

We commence by estimating the likelihood of strong lensing. An empirical value comes from the rate of observed strong-lensing in optical quasar or radio source surveys. In an attempt to control selection effects, the Jodrell-Bank VLA Astrometric Survey (JVAS) and the Cosmic Lens All-Sky Survey (CLASS) have conducted a statistically complete survey of over $15,000$ flat-spectrum radio sources (Brown & Myers 2000; Myers et al. 2001). With analysis almost complete, they have found 18 lensed sources, with 14 having source redshifts and image time delays that fall within the SNAP detectability range. Taken at face value (e.g. neglecting selection effects and population evolution), this would indicate that approximately 0.1% of SNe seen by SNAP would be expected to be strongly lensed, with image separations on the order of one arcsec and time delays between images ranging from a few days to over a year. As this statistic is based on a small number of strong lensing events, it is also instructive to look at theoretical calculations of the lensing rate. With this in mind we utilize the "stochastic universe method"

[1] see http://snap.lbl.gov for more information.

(SUM) to determine the probability for multiple imaging (Holz & Wald 1998). A key feature of this approach is that it accommodates lensing from *all* matter along the line of sight—possibly including the effects from thousands of galaxies—and in addition requires no assumptions regarding the luminosity-distance relation (Holz & Wald 1998; Bergström et al. 2000). It is to be emphasized, however, that the strong lensing results do not depend sensitively on the details of the methods, with differing analytic and numerical results being in good agreement (Turner, Ostriker, & Gott 1984; Holz, Miller, & Quashnock 1999; Metcalf & Silk 1999).

In Fig. 1 we show the probability of multiple-imaging of a given source (also referred to as the optical depth to strong lensing, τ) as a function of the source redshift, for a range of cosmologies. We take a conservative value of the dimensionless lensing efficacy parameter, $F = 0.025$ (Turner et al. 1984). The results are relatively insensitive to details of the mass function, and calculations with a PS distribution (Press & Schechter 1974) of galaxy masses yields similar results. Although taking all of the matter in the Universe to be in isothermal spheres is a great oversimplification, it is to be emphasized that effective modeling of many strong-lensing systems is accomplished with isothermal mass distributions (Koopmans & Fassnacht 1999; Witt, Mao, & Keeton 2000; Cohn et al. 2001).[2] Although NFW profiles (Navarro, Frenk, & White 1996) are expected to be a better approximation to the mass distribution of massive halos, baryons are expected to isothermalize the matter distributions for halos of galaxy mass and below (Kochanek & White 2001). Porciani & Madau (2000) have undertaken a study of lensing in cold dark matter universes with a PS distribution of galaxy masses, where NFW profiles are utilized for massive halos ($m > 3.5 \times 10^{13}\ \mathrm{M}_\odot$), and singular isothermal spherical profiles are used otherwise. Our extremely simplified model agrees with their results to within $\sim 20\%$. Our results are also consistent with the CLASS data.

Data in cosmology in recent years has been pointing to a "cosmic concordance" model (Bahcall et al. 1999), with $\Omega_m = 1/3$, $\Omega_\Lambda = 2/3$, and $H_0 = 70\ \mathrm{km\,sec^{-1}\,Mpc^{-1}}$, and we restrict our attention to this model in what follows. The likelihood results in Fig. 1 imply that 0.05% of sources at redshift $z = 1$ would be expected to be multiply imaged on arcsecond scales. At present roughly 100 high-z SNe have been observed (mostly at $z \approx 0.5$), and thus it is quite unlikely that any of them are multiply imaged. The situation is more bleak than the numbers indicate, however, as even if one of the observed high-z SNe happens to be multiply-imaged, it is exceedingly unlikely that we would stumble upon successive images.

The situation is much brighter if SNAP flies. SNAP's "optical" (0.35–1.0 μm) imager would observe 3,800 type Ia SNe per year, with detailed follow-up (restframe B-band photometry and spectra) of a subsample of 2,400 (100 at $z > 1.2$, and all at $z \leq 1.2$). By checking whether prior images have appeared nearby (within 15″) when selecting high-z SNe for follow-up, SNAP can assure that every multiply-imaged type Ia SN has at least one

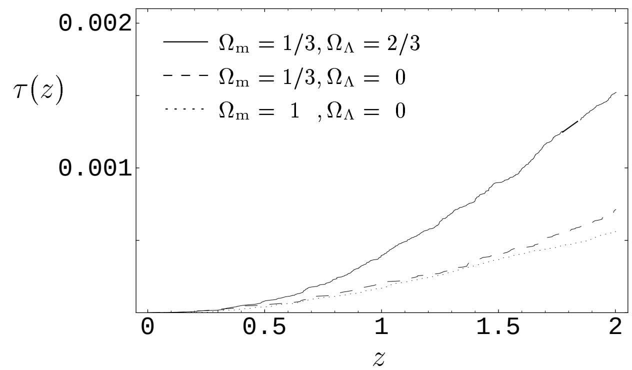

FIG. 1.— The optical depth, τ, to multiple imaging, as a function of redshift, z. Results for a range of cosmological parameters are shown, for a lensing efficacy of $F = 0.025$.

image with a redshift and absolute magnification determination. The ratio of the optical fluxes then allows a determination of the absolute magnification of all other images. Convolving the optical depth curve of Fig. 1 with the expected redshift distribution of SNAP SNe (relatively flat, with 1,500 type Ia's/year at $1.2 < z < 1.7$) yields an expectation of 2 multiply imaged Ia SNe per year.

SNAP would provide a homogeneously selected 28.5 (restframe U or B-band) magnitude-limited sample of all SNe which occur during its observation period in its 20 fixed 1 deg^2 fields of view, with two fields being additionally imaged down to a limiting magnitude of 30. Since the gap between deep images of each field will always be less than eight days, no SNe will fall through the observing cracks. Although the SNAP design is still in flux, we will take as one of its core requirements that all type Ia SNe with $z < 1.7$ will be discovered at least 3.8 magnitudes below peak brightness (and thus within ~ 2 rest frame days of the explosion). Therefore lensed images which have $> 3\%$ of the (unlensed) source flux will be observed. From our simplified SUM calculations, we find that 94% of strongly-lensed events are at least this bright. SNAP will see every type Ia SN out to redshift 1.7 in its deep fields, and will observe the vast majority of strong lensing events of these sources, thereby minimizing magnification bias in the strong lensing sample.

SNAP will also see a very large sample of type II SNe (though only a tiny fraction of these will have detailed follow-ups). While these are significantly dimmer (peak value 2.3 magnitudes below the Ia peak (in restframe B-band), with a dispersion of 1.3 mag (Gilliland, Nugent, & Phillips 1999)), they also occur at much higher rates (3 times more frequent at present day, rising to 5–10 times more frequent at redshift 1–2 (Sullivan et al. 2000)). Taking a conservative value of 5 times the Ia rate, we find that SNAP would have 10 multiply-imaged type II SNe in its sample per year. SNAP will catch the average SN II event only 1.5 magnitudes below peak, and so will miss images demagnified to less than 25% of the unlensed flux. Convolving the large intrinsic dispersion in type II peak brightness with the distribution of image pair magnifications (from our SUM calculations), we find that 60% of multiply-imaged type IIs will be observable, yielding an

[2] Singular isothermal spheres always produce double images, while roughly half of observed strong lensing systems are quads (Rusin & Tegmark 2001). Adding background shear, or considering singular isothermal ellipsoid lenses, produces the requisite quad images. Such generalizations can be expected to raise the optical depth curves in Fig. 1 (Schneider, Ehlers, & Falco 1992).

expected total of 6 events per year. For these systems, SNAP's optical imager light curve will provide a precise determination of the image time delays, separations, and relative fluxes. As one does not require the standard candle luminosities of lensed SNe to do strong-lensing science (see Sec. 4 and 5), strongly lensed type II systems are a valuable contribution to the lens database.

Combining the rate for SNe Ia and II, we conservatively estimate that SNAP would detect eight multiply-imaged SNe per year. Let us therefore assume that SNAP will fly, and explore the science that can be done with multiply-imaged SN systems.

3. DETECTION CRITERIA

A multiply-imaged SN would appear as successive SNe, closely clustered on the sky ($\lesssim 15''$). As gravitational lensing is achromatic, the light curves of the "different" SNe would be identical in all bands, modulo an overall amplification shift between the different images.[3] The probability of having a second SN appear in a given galaxy within one year is roughly equivalent to the multiple-imaging rate, and therefore well-sampled photometry of the light curves (to enable comparison of rise/fall parameters), or searches for lenses along the line of sight, will be required to positively identify lensing cases.

Characteristics of the SNAP mission impose a number of selection constraints on observable multiply-imaged SNe systems. The distribution of time delays between SN images can be expected to mimic those in multiply-imaged radio source and quasar surveys. From the theoretical distributions of time delays obtained via the SUM calculations, we find that 78% of strong lensing events have time delays such that they'd be seen in one year's observation, rising to 93% with three years of observation.

The angular resolution of SNAP is to be $0\farcs1$, which allows it to directly resolve the vast majority of image separations. An important possible systematic error for ground-based optical surveys of multiply-imaged systems is that images appearing near the center of the lens can be obscured by the lens (Porciani & Madau 2000). Because of SNAP's excellent angular resolution, and because baseline images of the galaxy without the supernovae will be available (and hence can be subtracted off), a SN image would be identifiable all the way into the core of a galaxy.

Even if the angular separation of SN images is well below the resolution limit of the SNAP telescope (which is exceedingly unlikely for macrolensing cases), because the SNe are transitory we may nonetheless be able to see and distinguish images. As long as the light curves do not significantly overlap in time, proximity (and blending) of images is no impediment to observation. In addition, it is straightforward to associate even very widely spaced images, as we expect to see all SNe within SNAP's large ($1\ \mathrm{deg}^2$) field of view (limited to systems with time delays which fall within the SNAP observational period).

The likelihood results are quite sensitive to the form of the dark matter. Thus far we have been considering smoothly distributed isothermal halos filled with microscopic dark matter (e.g. axions, WIMPS). If a significant ($\gtrsim$10%) fraction of halo matter is in macroscopic form (e.g. MACHOs, black holes), the lensing probability increases dramatically due to frequent microlensing (Schneider & Wagoner 1987; Rauch 1991). At cosmological distances, lensing by compact objects with masses below $10^6\,M_\odot$ produces image separations of less than a few milliarcseconds and time delays of less than a minute, indicating that multiple imaging would no longer be directly discernible. The overall amplification of the combined image would still be noticeable down to lens mass scales of $\sim 10^{-4}\,M_\odot$, below which the SN can no longer be treated as a point source (linear extent $\sim 10^{15}$ cm corresponds to an angular size on the order of the Einstein angle of the lens), and lensing ceases to have an effect. In addition, if there is relative motion between the lens and the line of sight to the source, the amplification becomes time dependent. The lensing timescale at cosmological distances goes as $\delta t \sim 18$ days$\,(10^9\ \mathrm{cm\,sec^{-1}}/v)\sqrt{(}M/10^{-3}\,M_\odot)$, with v the expansion velocity of the SN, and m the mass of the compact lens. Therefore lenses in the mass range $10^{-4}\,M_\odot \lesssim m \lesssim 10^{-3}\,M_\odot$ can produce a MACHO-type signal superposed on the SN light curve. Microlensing by compact objects with $m \gtrsim 10^{-3}\,M_\odot$ will manifest itself as an overall amplification shift of the (standard candle) light curve, inducing further scatter in the SN Hubble diagram (Minty, Heavens, & Hawkins 2001).

4. INDEPENDENT MEASURE OF COSMOLOGICAL CONSTITUTION

Over the course of a few years, SNAP would provide a uniformly selected survey of many thousands of SNe, offering the possibility of a variety of statistical tests of cosmology. For example, the different curves in Fig. 1 should be distinguishable observationally—three years' data would differentiate between $\Omega_\Lambda = 2/3$ and $\Omega_\Lambda = 0$ at better than 3σ. That the SNe are standard candles is completely irrelevant to determining cosmology via lensing likelihood, and thus strong lensing provides a powerful independent probe, and consistency check, for the SN measurement of the distance-redshift relation (the primary mission of SNAP).

In addition, the strong lensing likelihood depends upon the clumpiness of the dark matter, and thereby allows the distinction between microscopic and macroscopic dark matter (Linder et al. 1988). Furthermore, Wyithe et al. (2001) have suggested that the optical depth to multiple imaging could be used to distinguish between interacting and non-interacting dark matter. A complementary cosmological measurement is offered by the distribution of image separations and lensing image morphologies (Keeton, Kochanek, & Seljak 1997; Rusin & Ma 2001; Kochanek & White 2001). These approaches are less sensitive to the cosmological parameters, but quite sensitive to the mass distribution within halos.

5. INDEPENDENT MEASURE OF COSMOLOGICAL SCALE

Multiply-imaged systems allow for the determination of the Hubble constant, H_0, through the measurement of

[3] Extinction along different lines of sight could yield a chromatic difference between multiple images of a given SN. However, because of the extensive phenomenological knowledge of type Ia SN light curves and colors (Riess, Press, & Kirshner 1996a,b), the extinction in a given image is quantifiable to within $\lesssim 0.04$ mag, sharply reducing the likelihood of false dissociations. Having multiple images sampling different lines of sight through a galaxy or cluster could provide a rudimentary map of the distribution of dust in the lens.

time delays between images (Refsdal 1964). This method has been developed for over a decade in multiply-imaged quasar systems, with varying success (Koopmans & Fassnacht 1999). One of the limitations of such systems is that the time delays can often be quite difficult to determine (Kundić et al. 1997). In the case of multiply-imaged SNe the determination of the time delay will be completely straightforward, as the time of peak luminosity of a given SN will be determined to an accuracy of better than a day as an integral part of the SNAP observing program. It is also often difficult to determine the flux ratio of the images with good accuracy (due to time variability of the source, extinction, etc.; see Mao & Schneider (1998)). As SNe light curves have been extensively characterized, the flux ratios will be well determined.

It is often the modeling of the lens that limits the precision of the determination of H_0 (Keeton et al. 2000; Cohn et al. 2001). A major impediment to constraining lens profiles is the limited number of constraints a lens system provides (at best, a handful of image separations, relative brightnesses, and time delays). Attempts to increase the number of constraints generally rely on utilizing lensed images of the extended background galaxy (arcs, Einstein rings, etc.; see Keeton et al. (2000); Kochanek, Keeton, & McLeod (2001)). For quasars these attempts can be hindered by the large brightness contrast between the quasar source and the rest of the host galaxy. In the case of SNe, however, the images conveniently turn themselves off, allowing an uncontaminated view of the host. To establish a baseline for the light "contamination" to the SN curve from the host galaxies, SNAP will make deep images of the hosts both before the SNe appear and after they fade away. Subsequent very deep observations with a variety of different instruments (e.g. NGST, CELT+AO) at a range of wavelengths could also be made. These images of the *lensed* host galaxy would provide important additional constraints to the lens model. It is again to be emphasized that the measure of H_0 with time delays is independent of the standard-candleness of the SNe, and is thus completely independent of Cepheid-based measurements of the Hubble constant with type Ia SNe (Jha et al. 1999).

6. BREAKING THE MASS SHEET DEGENERACY

Although the science in the preceding sections does not depend on the SNe being standard candles, this property can have important consequences for lensing studies. A drawback of many lensing analyses done to date is that they suffer from a mass-sheet degeneracy: a uniform sheet of matter anywhere between the source and observer will generally remain undetected. Because type Ia (and to a lesser degree type II) SNe are standard candles, the *absolute* magnification can be determined, yielding an additional constraint (by changing the relative fluxes of all images into absolute fluxes), and breaking this degeneracy (Kolatt & Bartelmann 1998).

An additional feature of SNAP is that, in the course of returning to the same fields week after week looking for new SNe, it will make very high quality weak lensing maps. Coupling information from both weak and strong lensing studies of a given field may yield additional insights—for example, a mass concentration which causes a large-separation multiple-imaging event may also be detectable in the weak lensing map of the same field. Any SNe (strongly lensed or not) superposed on a weak lensing map will (in principle) allow for a breaking of the mass sheet degeneracy.

7. CONCLUSIONS

The observation of multiply-imaged SNe would afford independent measurements of cosmological parameters. Although current high-z SN surveys are unlikely to observe a multiply-imaged SN system, SNAP would be expected to see at least eight such events per year. These systems would be a boon to science, independent of and in addition to the primary goals of SNAP.

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